Using MMX™ Instructions to Implement Viterbi Decoding

Information for Developers and ISVs

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CONTENTS

1.0. INTRODUCTION

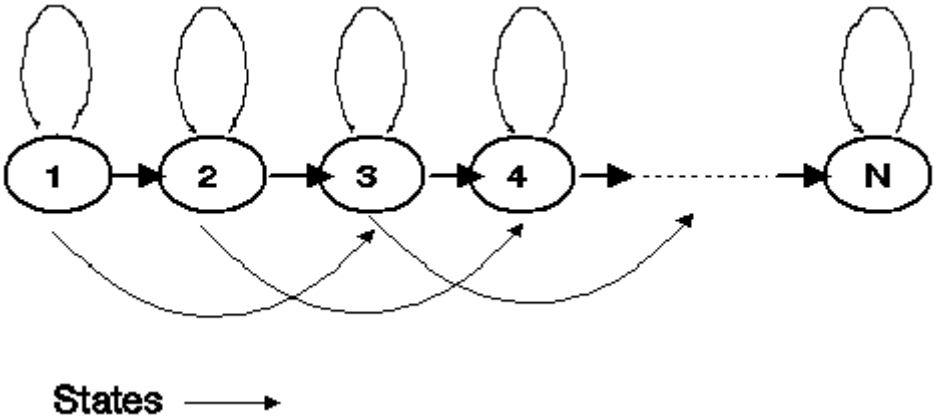
The Intel Architecture (IA) media extensions include single-instruction, multi-data (SIMD) instructions. This application note presents a code example that implements the Viterbi decoding algorithm. These extensions include single-instruction multiple-data (SIMD) instructions that can operate in parallel on eight-byte (8-bit) operands, four-word (16-bit) operands or two long (32-bit) operands. Using these instructions, the Viterbi decoding algorithm shows a performance gain of 2X, over normal IA (scalar) code, because the data is manipulated 64-bits at a time. In this implementation, 32-bit operands are used, therefore two such operands can be manipulated (add, subtract etc.) in parallel in a single clock cycle.

1.1. The Viterbi Decoding Algorithm

In this section a very brief description of Hidden Markov Models (HMM) and the Viterbi algorithm is given. The reader is encouraged to consider the references listed in Section 1.2. for a more detailed coverage of this topic and its relationship to speech recognition.

Viterbi decoding is a Dynamic Programming (DP) algorithm that, among other applications, is used in evaluating Hidden Markov Models. An HMM consists of N states where transitions can occur from one state i to another state j with a probability a(j,i) called the *transition probability*. The probability of being in state i at time t = 1 is $\pi(\iota)$ and is called the *initial probability*. When the constraint a(j,i) = 0 for j > i + 2 applies, then the HMM is known as a constrained-jump model and is frequently used for speech recognition. The connectivity of such a model is shown in Figure 1. Note the transitions from state 1 to states 1, 2, and 3 but not to 4.

Figure 1. Hidden Markov Model (Constrained-Jump)



When modeling speech on a transition occurring to state j at time t, a continuous output observation O(t) (usually a speech feature vector) is generated with a probability b(i,O(t)) called the *output probability*. In a discrete HMM, the continuous observation vector O(t) is Vector Quantisized (VQ) to a single discrete VQ index k(t) that is then used to lookup the output probability b(i,k(t)). Frequently, this is written in short form as b(i, t).

Thus, given an observation sequence O(t), t = 1..T, one can compute the probability that the observation sequence can be generated by a given HMM. There will be many paths (i.e. state sequences) in the HMM that can generate the same observation sequence - however, with different probabilities.

The Viterbi decoding algorithm computes the probability of the best (highest probability) path including (optionally) the sequence of states in the best path. This probability is known as the Viterbi probability P^V which can be computed for an observation sequence O(t), t = 1,..,T as

$$P^V = \text{Max}\{\phi(j, T)\}, \text{ max over states } j = 1,..,N$$

where $\phi(j, t)$ is computed using the recursive pair

$$\phi(j, t+1) = \text{Max}_{i=1,N}\{ \phi(i, t) * a(j,i)\} * b(j, O(t+1))\}, t = 1,2,..,T-1, \text{ max over states } i = 1,..,N$$

Initialization is done using

$$\phi(j, 1) = \pi(j) * b(j, O(1)), j = 1,..,N$$

In this implementation, negative log probabilities (base 10) are used (so we end up with all positive numbers) because then the multiplication changes to an addition, mitigating the scaling issues. Furthermore, only the constrained-jump model discrete HMM is assumed. Therefore, taking negative logarithms on each side the above three equations reduce to:

$$-\log(P^V) = \text{Min}\{-\log(\phi(j, T))\}, \text{ min over states } j = 1,..,N$$

$$-\log(\phi(j, t+1)) = \text{Min}\{-\log(\phi(i, t)) - \log(a(j,i))\} - \log(b(j, k(t+1)), t = 1,2,..,T-1, \text{ min over states } i = j, j - 1, j - 2$$

$$-\log(\phi(j, 1)) = -\log(\pi(j)) - \log(b(j, k(1)))$$

Using the notation :

$$Dist^V == -\log(P^V), Dist(j, t) == -\log(\phi(j, t)), aProb(j, i) == -\log(a(j,i)), bProb(j, k(t)) == -\log(b(j, k(t)) \text{ and } iProb(j) == -\log(\pi(j))$$

we get the following three important equations:

Initialization:

$$Dist(j, 1) = iProb(j) + bProb(j, k(1)), j = 1,..,N \quad \textbf{(1)}$$

Iteration:

$$Dist(j, t+1) = \text{Min}\{Dist(i, t) + aProb(j, i)\} + bProb(j, k(t+1)), t = 1,2,..,T-1, \text{ min over states } i = j, j-1, j-2 \quad \textbf{(2)}$$

Final Computation:

$$Dist^V = \text{Min}\{Dist(j, T)\}, \text{ min over states } j = 1,2,..,N \quad \textbf{(3)}$$

Sometimes it might be desirable to store the best path sequence also in addition to the best path distance. In this implementation only the best path distance is computed.

Figure 2. Viterbi Lattice

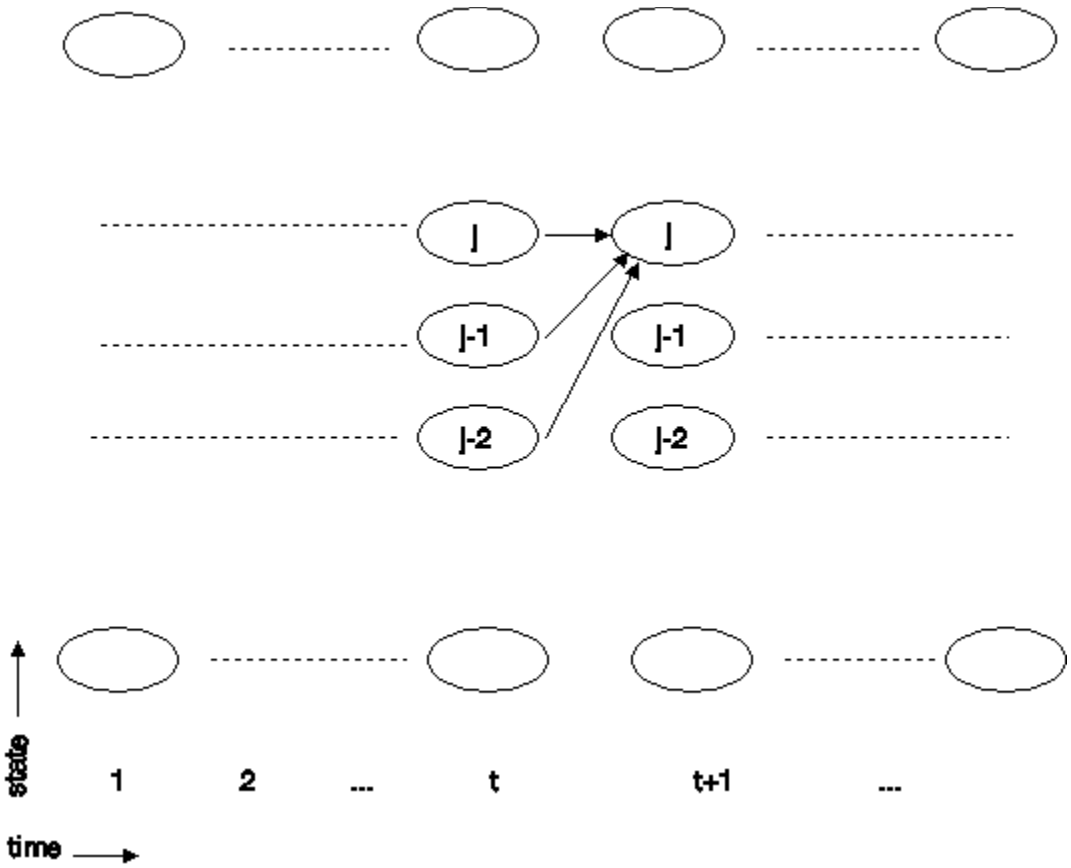


Figure 2. shows the lattice that is used to compute equation (2). At each time index this computation is done for all states (i.e. for j = 1 to N).

1.2. HMM References

For a detailed description of HMMs and the Viterbi algorithm see Rabiner, L. R., "A Tutorial on Hidden Markov Models and Selected Applications in Speech Recognition," Proceedings of the IEEE 1989. Another excellent reference is "Readings in Speech Recognition," edited by A. Waibel and K. F. Lee, Morgan Kaufmann Publishers, Inc. San Mateo, CA, copyright 1990. A comprehensive reference on HMMs and speech technology in general is "Discrete-Time Processing of Speech Signals," authored by J. R. Deller, J. G. Proakis, and J. H. L. Hansen, Macmillan Publishing Company.

2.0. THE VITERBI_MMX FUNCTION

The viterbi_mmx function implements equations (1), (2) and (3) shown in the previous section with an optimized core for equation (2) where the bulk of the computation is done. The function takes as input seven arguments in the following order:

1. obsVect the observation vector containing the VQ indices for time t = 1..T.
2. obsLen the length of the observation sequence = T.
3. aProb the transition probability matrix represented as a vector. The format will be described later.
4. bProb the output probability matrix with nStates rows and nSymbols columns. bProb (j, m) represents the probability of outputting the symbol with VQ index m while in state j.
5. iProb the initial probability vector. Here iProb(j) represents the initial probability of state j.
6. nStates the number of states in the HMM.
7. distBuffer a temporary buffer to store the accumulated Dist quantities. This should be of length nstates + 2.

It is assumed that aProb, bProb, and iProb are range limited to 16-bits. However, to prevent overflow when using (2), Dist is computed using 32-bits in the provided data structure buffer. This allows obsLen to be long enough for most practical purposes without causing overflow in (2). In order to avoid frequent unpacking of data, aProb, bProb, and iProb are also required to be 32-bit numbers (although range limited to 16-bits, i.e., the high order 16 bits of these datums are zeros). The vectors obsVect and buffer are also 32-bit vectors.

2.1. Core of viterbi_mmx

From equation (2) and Figure 2. it is apparent that when j > 2, each Dist at time t is computed as from three previous values of Dist at time t-1 as follows.

$$Dist(j, t) = Min\{(Dist(j, t-1) + aProb(j, j)), (Dist(j, t-1) + aProb(j, j-1)), (Dist(j, t-1) + aProb(j, j-2))\} + bProb(j, k(t))$$

By computing Dist(j,t) using decreasing values of j (from j = N down to 1), the computation can be done in-place because each Dist(j, t+1) does not use Dist(i, t) for states i > j. Because MMX™ instructions can operate on two 32-bit operands at a time we can compute Dist(j, t) and Dist(j-1, t) at the same time (i.e. two states at a time). However, it turns out that doing so results in a suboptimal implementation in terms of instruction pairing opportunities. Therefore the core implementation processes four Dist values, viz. Dist(j, t), Dist(j-1, t), Dist(j-2, t), at Dist(j-3, t) in a single iteration of the loop. This computation is shown in Example 1. Each column in the first three pairs of rows shows the aProb value that gets added to the Dist value. After the addition, the minimum of these three pairs of rows is taken which then gets added to the bProb values shown in the last line. Processing four states at a time allows for almost every instruction to get paired after rescheduling the instructions, thereby increasing the throughput of the core implementation. Example 2. shows the implementation prior to pairing and rescheduling the instructions. This code takes 33 clocks per loop iteration - working out to about 8.25 clocks per HMM state. Example 3. shows the same code after rescheduling and pairing the instructions resulting in a peak throughput of about 24 clocks per loop iteration of four states - working out to 6 clocks per HMM state. Some of the address arithmetic has been changed in order to facilitate pairing. In Examples 2 and 3, any instruction that gets paired with the next instruction is shown with a leading "p".

All the eight MMX registers MM0 to MM7 and all the available integer registers are used in the core implementation. Mnemonics are used for the integer register names for readability. The registers bAddrReg, aAddrReg and distAddrReg are used to store the pointers for aProb, bProb and Dist respectively. The memory location nCount and the register nCountReg contain the quotient on dividing nStates by 4. The core iterates until nCountReg is decremented to 0. The memory location nRemain contains the number of states remaining (0, 1, 2 or 3) after processing the states four at a time. Code segments (see the assembly listing) are provided to optimally process these remaining states after the core has completed execution for a single time index. The register obsNoReg contains the address of the next observation symbol index to process.

Example 1. Processing Four States at a Time

```
..Dist(j, t)     Dist(j-1, t)            Dist(j-2, t)            Dist(j-3, t)..
..aProb(j, j)    aProb(j-1, j-1)         aProb(j-2, j-2)         aProb(j-3, j-3)..
..Dist(j-1, t)   Dist(j-2, t)            Dist(j-3, t)            Dist(j-4, t)..
..aProb(j, j-1)  aProb(j-1, j-2)         aProb(j-2, j-3)         aProb(j-3, j-4)..
..Dist(j-2, t)   Dist(j-3, t)            Dist(j-4, t)            Dist(j-5, t)..
..aProb(j, j-2)  aProb(j-1, j-3)       aProb(j-2, j-4)           aProb(j-3, j-5)..
..bProb(j, t)    bProb(j-1, t)           bProb(j-2, t)           bProb(j-3, t)
```

The data structure aProb is stored in blocks of 6 values in sequence, viz. aProb(j, j), aProb(j-1, j-1), aProb(j, j-1), aProb(j-1, j-2), aProb(j, j-2), and aProb(j-1, j-3). Then the next 6 values aProb(j-2, j-2), aProb(j-3, j-3), and so on are stored. The connectivity of states 1 and 2 is different from the other states. For example, state 1 can have an incoming transition only from state 1 and state 2 can have incoming transitions from states 2 and 1. All other states have three incoming transitions. For this reason the data structure aProb needs to be padded with a large value (HI) which allows the same core loop to be used for these states - essentially working like a "don't care' because of taking the minimum. Similarly the Dist data structure needs to be padded with two extra HI values to allow the last four states to be processed by the core loop. The assembly listing contains the optimized instruction sequences when the number of final remaining states are 1, 2 or 3 (i.e. the number of states nStates in the model is not a multiple of 4).

The core contains instruction sequences including logical instructions such as pxor, pand etc. These are for computing the minimum which is described in the next section.

Example 2. Core of viterbi_mmx (Preliminary - Minimum Pairing)

```
FourStateLoop:
     movq mm0, [distAddrReg]         ; Move Dist(j, t) & Dist(j-1, t) to mm0
     movq mm2, [distAddrReg + 4]     ; Move Dist(j-1, t) & Dist(j-2, t) to mm2
     movq mm1, [distAddrReg + 8]     ; Move Dist(j-2, t) & Dist(j-3, t0 to mm1
     movq mm3,  mm1                  ; Move Dist(j-2, t) & Dist(j-3, t) to mm3
     movq mm5, [distAddrReg + 12]    ; Move Dist(j-3, t) & Dist(j-4, t) to mm5
     movq mm4, [distAddrReg + 16]    ; Move Dist(j-4, t) & Dist(j-5, t) to mm4
     paddd mm0, [aAddrReg]           ; Add aProb(j, j) & aProb(j-1, j-1) to mm0
     paddd mm2, [aAddrReg + 8]       ; Add aProb(j, j-1) & aProb(j-1, j-2) to mm2
     paddd mm1, [aAddrReg + 16]      ; Add aProb(j, j-2) & aProb(j-1, j-3) to mm1
p    movq mm7,  mm1                  ; Get the minimum of mm1 and mm2 into mm1
     pcmpgtd mm1, mm2                ; minimum contd.
     pxor mm2, mm7                   ; minimum contd.
     pand mm1, mm2                   ; minimum contd.
p    pxor mm1,  mm7                  ; minimum done
     movq mm7,  mm0                  ; Get the minimum of mm0 and mm1 into mm0
p    pcmpgtd mm0, mm1                ; minimum contd.
     pxor  mm1, mm7                  ; minimum contd.
     pand mm0, mm1                   ; minimum contd.
     pxor mm0, mm7                   ; minimum done
     paddd mm0, [bAddrReg]           ; Add bProb(j, t) & bProb(j-1, t) to mm0
```

```
     movq [distAddrReg], mm0         ; Move mm0 to Dist(j, t) & Dist(j-1, t)
     paddd mm3, [aAddrReg + 24]      ; Add aProb(j-2, j-2) & aProb(j-3, j-3) to mm3
     paddd mm5, [aAddrReg + 32]      ; Add aProb(j-2, j-3) & aProb(j-3, j-4) to mm5
     paddd mm4, [aAddrReg + 40]      ; Add aProb(j-2, j-4) & aProb(j-3, j-5) to mm4
p    movq mm7, mm4                   ; Get the minimum of mm4 and mm5 into mm4
     pcmpgtd mm4, mm5                ; minimum contd.
     pxor mm5, mm7                   ; minimum contd.
     pand mm4, mm5                   ; minimum contd.
p    pxor mm4, mm7                   ; minimum done
     movq mm7, mm3                   ; Get the minimum of mm3 and mm4 into mm3
p    pcmpgtd mm3, mm4                ; minimum contd.
     pxor mm4, mm7                   ; minimum contd.
     pand mm3, mm4                   ; minimum contd.
     pxor mm3, mm7                   ; minimum done
     paddd mm3, [bAddrReg + 8]       ; Add bProb(j-2, t) & bProb(j-3, t) to mm3
p    movq [distAddrReg + 8], mm3     ; Move mm3 to Dist(j-2, t) & Dist(j-3, t)
     add aAddrReg, 48                ; Advance aProb to the next block
p    add distAddrReg, 16             ; Advance Dist to the next four states
     add bAddrReg, 16                ; Advance bProb to the next block
p    dec nCountReg                   ; Decrement count register
     jz checkLastStates              ; If count register is zero then check remaining states
     jmp FourStateLoop               ; Loop back to FourStateLoop
```

Example 3. Core of viterbi_mmx (Final - After Rescheduling and Pairing)

```
FourStateLoop:
     movq mm1, [distAddrReg + 8]
p    movq mm0, [distAddrReg]
     movq mm3, mm1
     paddd mm1, [aAddrReg + 16]
p    movq mm2, [distAddrReg + 4]
     movq mm7, mm1
     paddd mm2, [aAddrReg + 8]
p    paddd mm0, [aAddrReg]
     pcmpgtd    mm1, mm2
p    movq mm5, [distAddrReg + 12]
     movq mm6, mm0
p    movq mm4, [distAddrReg + 16]
     pxor mm2, mm7
p    paddd mm4, [aAddrReg + 40]
     pand mm1, mm2
p    paddd mm3, [aAddrReg + 24]
     pxor mm1, mm7
p    paddd mm5, [aAddrReg + 32]
     pcmpgtd    mm0, mm1
p    pxor mm1, mm6
     movq mm7, mm4
p    pcmpgtd    mm4, mm5
     pand mm0, mm1
p    pxor mm5, mm7
     pxor mm0, mm6
p    paddd mm0, [bAddrReg]
     pand mm4, mm5
p    pxor mm4, mm7
     movq mm6, mm3
p    movq [distAddrReg], mm0
     pcmpgtd    mm3, mm4
p    pxor mm4, mm6
     add bAddrReg, 16
```

```
p    pand mm3, mm4
     add distAddrReg, 16
     pxor mm3, mm6
     paddd mm3, [bAddrReg - 8]
p    add aAddrReg, 48
     dec nCountReg
     movq [distAddrReg - 8], mm3
p    cmp nCountReg, 0
     jz checkLastStates
     jmp FourStateLoop
```

2.2. Finding the Minimum

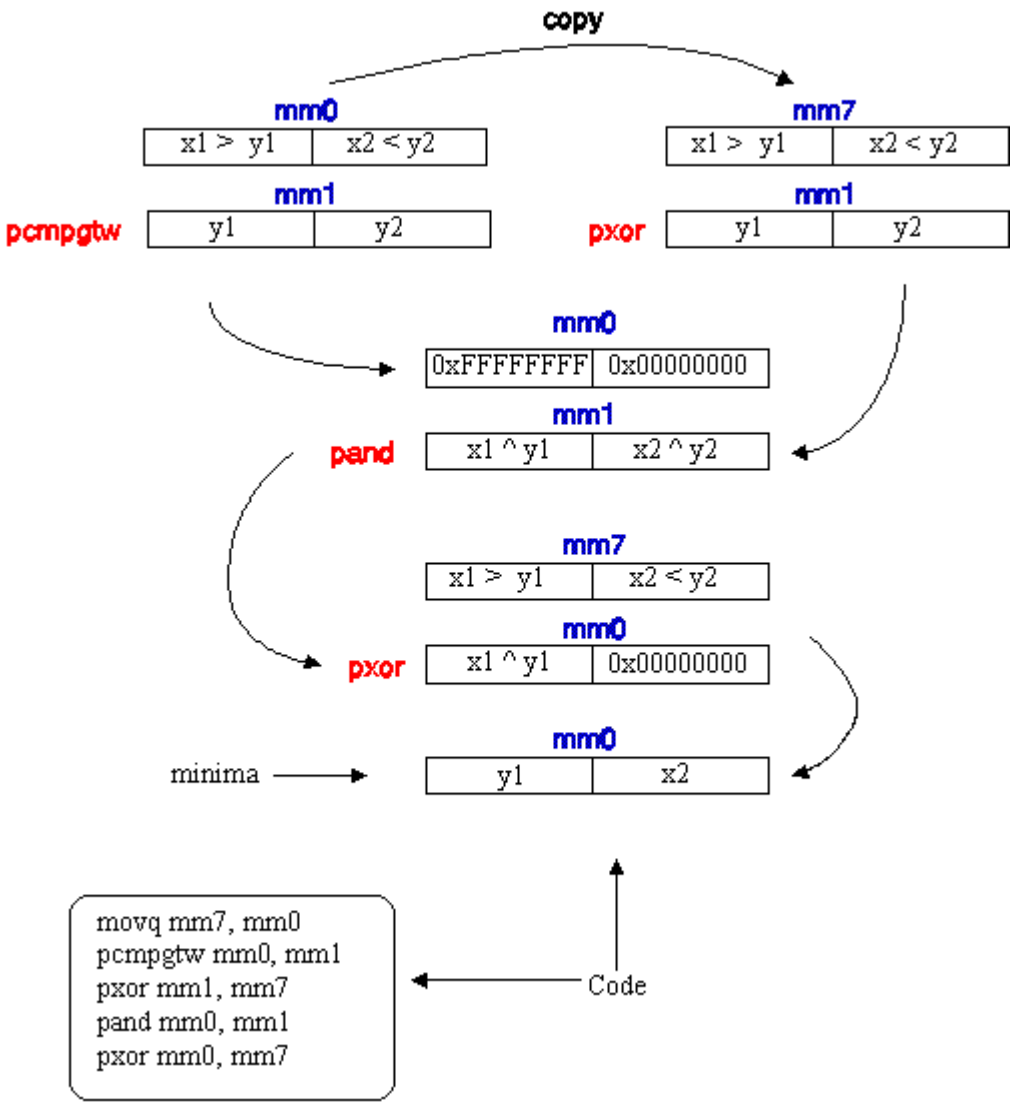
The Viterbi core described above requires the determination of the minimum of two multimedia registers. The technique used to accomplish this relies on the observation that two values A and B can be swapped using a sequence of Xor operations e.g.

```
C  <--  A  XOR B
B  <--  C XOR B
A  <--  A XOR C
```

After the sequence of Xor operations show above, A contains the original value of B and B contains the original value of A.

The method is now illustrated with an example. Assume [x1, x2] and [y1, y2] are the contents of registers mm0 and mm1 (x1, x2, y1, and y2 are all 32-bit numbers) then we would like to get [min(x1,y1), min(x2,y2)] into register mm0. The method uses the Packed Comparison operation (pcmpgt) and the two logical operations Packed And (pand) and Packed Xor (pxor) to sort the inputs x1, x2, y1, and y2. Figure 3. shows the code fragment and the sequence of operations diagrammatically assuming that x1 > y1 and x2 < y2. The correct result, therefore, would be [y1, x2] in register mm0. The register mm7 is used as a temporary register.

Figure 3. Finding the Minimum



2.3. Alignment of Operands

It is important for the data structures passed to the viterbi_mmx function to be aligned to 8 byte boundaries. The viterbi_mmx function assumes that the data is already properly aligned. There is a penalty associated with misaligned data which can severely degrade the performance of the function. The C code listing provided in Section 4.0 here does not align the data. Either the alignment can be done during allocation or can be done after allocation by shifting the data structure such that it gets properly aligned. This shifting can be done by a simple routine.

3.0. PERFORMANCE GAINS

This section compares the performance of the viterbi_mmx core function with an estimate of the same core implemented using scalar instructions. In computing the performance we assume ideal conditions of all data in cache and no misaligned accesses.

The viterbi_mmx core processes four states every 24 clock cycles. This works out to 6 clocks for every state. Example 4. shows (in pseudo-code) what would be required in order to write the core using scalar instructions to process a single state.

Example 4. Scalar Code (Pseudo-Code)

```
core:
1.      Move Dist(j, t) to Register1
2.      Move Dist(j-1, t) to Register2
3.      Move Dist(j-2, t) to Register3
4.      Add aProb(j, j) to Register1
5.      Add aProb(j, j-1) to Register2
6.      Add aProb(j, j-2) to Register3
7.      Find Minimum of Register1, Register2 and Register3 into Register1
8.      Add bProb(j, t) to Register1
9.      Write Register1 to Dist(j, t)
10.     Decrement nCountReg
11.     Jump to CheckLastStates if nCountReg is zero
12.     Jump to core
```

Here Steps 1 to 3 involve a move instruction with memory operand. Steps 4 to 6 involve an add instruction with a memory operand. Steps 8 and 9 each involve an add instruction and a move instruction respecively, each with a memory operand. Steps 10 and 11 involve pairable instructions. Step 7 involves at least six instructions (two sets of compare, move and test-and-jump instructions). So even in the best case assuming we unroll the loop to process two states at a time we can pair only the six instructions at Step 7. So our instruction count to process a single state for the best scheduled code becomes 3 (steps 1-3) + 3 (steps 4-6) + 3 (step 7) + 2 (steps 8, 9) + 1 (steps 10, 11) + 1 (step 12) i.e. a total of 13 clocks. Note that this is only an estimate and probably represents the best case.

In summary the MMX code performs slightly better than 2X times the scalar code. This can be explained by the fact that the MMX code is manipulating two 32-bit operands in a single clock cycle while the scalar code is manioperating only on a single 32-bit operand in a manipulating a single 32-bit operand in one clock cycle.

4.0. CODE LISTINGS

This section contains the assembly and C code listings. The assembly code implements the viterbi_mmx function using MMX instructions. The C code contains a straight C code implementation (viterbi_c) of the same Viterbi function for testing purposes. The main program in the C listing executes and compares the MMX code and C code implementations for a few small data sets (the results for both versions, should, naturally, be the same). The results of the comparisons are printed out to the standard console output.

Example 5 shows the assembly code listing and Example 6 the C code listing.

Example 5. Assembly Code Listing

```
        TITLE   viterbi.asm
        .486P
.model FLAT
PUBLIC_ _viterbi_mmx
_DATA   SEGMENT
_DATA   ENDS
_TEXT   SEGMENT
_obsVect$ = 8
_obsLen$ = 12
_aProb$ = 16
_bProb$ = 20
_pi$ = 24
_nStates$ = 28
_dist$ = 32
_obsNo$ = -4
_nCount$ = -8
_nRemain$ = -12
bAddrReg        EQU     ebx
aAddrReg EQU    ecx
nCountReg       EQU     edx
nCount          EQU     DWORD PTR _nCount$[ebp]
distAddrReg     EQU     esi
obsNoReg EQU    edi
nRemain  EQU DWORD PTR _nRemain$[ebp]
_viterbi_mmx    PROC NEAR
        push    ebp
        mov     ebp, esp
        sub esp, 12
        push    esi
        push    edi
        cmp DWORD PTR_obsLen$[ebp], 0
        jle done
        cmp DWORD PTR_nStates$[ebp], 0
        jle done
        ; For each state i, initialize dist[i] = pi[i] + b[obsVect[0]][i]
        ;
        mov esi,_bProb$[ebp]
        mov eax,_obsVect$[ebp]
        mov eax, [eax]
        mov  esi, [esi + eax*4]
        xor eax, eax
        mov ebx,_dist$[ebp]
        mov ecx,_pi$[ebp]
init:
        mov edx, [ecx + eax*4]
        add edx, [esi + eax*4]
```

```
        mov [ebx + eax*4], edx
        inc eax
        cmp eax,_nStates$[ebp]
        jne init

        mov obsNoReg, 1
        ; The states are processed four at a time. The number of quads to process
        ; is saved in nCount and nCountReg. The number of remaining states
        ; (i.e. 0, 1, 2 or 3) is saved in nRemain.
        mov nCountReg,_nStates$[ebp]
        cmp nCountReg, 0
        je done
        shr nCountReg, 2
        mov nCount, nCountReg
        mov ebx, nCountReg
        shl ebx, 2
        mov eax,_nStates$[ebp]
        sub eax, ebx
        mov nRemain, eax
mainLoop:
        ; Main loop for advancing the time index. For each
        ; time index process four states at time in FourStateLoop:
        ; Exit if end of observations
        ;
        cmp obsNoReg,_obsLen$[ebp]
        je done
        ; Move addresses and count register
        ;
        mov aAddrReg,_aProb$[ebp]
        mov distAddrReg,_dist$[ebp]
        mov nCountReg, nCount
        ; Move to bAddrReg the row address
        ; for the current observation symbol
        ;
        mov bAddrReg,_bProb$[ebp]
        mov eax,_obsVect$[ebp]
        mov eax, [eax + obsNoReg*4]
        mov  bAddrReg, [bAddrReg + eax*4]
        inc obsNoReg
        cmp nCountReg, 0
        je checkLastStates
FourStateLoop:
        ; Core loop to process four states at a time
        ; for a given time index.
        movq mm1, [distAddrReg + 8]
        movq mm0, [distAddrReg]
        movq mm3, mm1
        paddd mm1, [aAddrReg + 16]
        movq mm2, [distAddrReg + 4]
        movq mm7, mm1
        paddd mm2, [aAddrReg + 8]
        paddd mm0, [aAddrReg]
        pcmpgtd  mm1, mm2
        movq mm5, [distAddrReg + 12]
        movq mm6, mm0
        movq mm4, [distAddrReg + 16]
        pxor mm2, mm7
        paddd mm4, [aAddrReg + 40]
        pand mm1, mm2
        paddd mm3, [aAddrReg + 24]
        pxor mm1, mm7
        paddd mm5, [aAddrReg + 32]
        pcmpgtd  mm0, mm1
        pxor mm1, mm6
```

```
        movq mm7, mm4
        pcmpgtd  mm4, mm5
        pand mm0, mm1
        pxor mm5, mm7
        pxor mm0, mm6
        paddd mm0, [bAddrReg]
        pand mm4, mm5
        pxor mm4, mm7
        movq mm6, mm3
        movq [distAddrReg], mm0
        pcmpgtd  mm3, mm4
        pxor mm4, mm6
        add bAddrReg, 16
        pand mm3, mm4
        add distAddrReg, 16
        pxor mm3, mm6
        paddd mm3, [bAddrReg - 8]
        add aAddrReg, 48
        dec nCountReg
        movq [distAddrReg - 8], mm3
        cmp nCountReg, 0
        jz checkLastStates
        jmp FourStateLoop
checkLastStates:
        ; Check the remaining number of states
        ; and process appropriately
        mov nCountReg, nRemain
        cmp nCountReg, 1
        je lastState
        cmp nCountReg, 2
        je lastTwoStates
        cmp nCountReg, 3
        je lastThreeStates
        jmp mainLoop
lastThreeStates:
        ; Three states left to process
        movq mm0, [distAddrReg]
        movq mm2, [distAddrReg + 4]
        movq mm1, [distAddrReg + 8]
        paddd mm1, [aAddrReg + 16]
        paddd mm0, [aAddrReg]
        movq mm7, mm1
        paddd mm2, [aAddrReg + 8]
        movq mm6, mm0
        pcmpgtd  mm1, mm2
        pxor mm2, mm7
        pand mm1, mm2
        pxor mm1, mm7
        pcmpgtd  mm0, mm1
        pxor mm1, mm6
        pand mm0, mm1
        pxor mm0, mm6
        paddd mm0, [bAddrReg]
        add aAddrReg, 24
        add bAddrReg, 8
        movq [distAddrReg], mm0
        add distAddrReg, 8
        jmp lastState
lastTwoStates:
        ; Two states left to process
        movq mm0, [distAddrReg]
        movq mm2, [distAddrReg + 4]
        ; Process the last two states
        ;
```

```
        paddd mm0, [aAddrReg]
        paddd mm2, [aAddrReg + 8]
        ; Get the minimum of mm0 and mm2 into mm0
        movq mm7, mm0
        pcmpgtd  mm0, mm2
        pxor mm2, mm7
        pand mm0, mm2
        pxor mm0, mm7
        paddd mm0, [bAddrReg]
        movq [distAddrReg], mm0
        jmp mainLoop
lastState:
        ; Only one state left to process
        mov eax, [distAddrReg]

        add eax, [aAddrReg]
        add eax, [bAddrReg]
        mov [distAddrReg], eax
        jmp mainLoop
done:
        ; Find the minimum dist[i] for all states i and return in eax
        ;
        mov distAddrReg, _dist$[ebp]
        mov eax, [distAddrReg]
        mov ebx, 1
        cmp ebx, _nStates$[ebp]
        je exit
minLoop:
        cmp eax, [distAddrReg + ebx*4]
        jle noSwitch
        mov eax, [distAddrReg + ebx*4]
noSwitch:
        inc ebx
        cmp ebx, _nStates$[ebp]
        jne minLoop
exit:
        pop     edi
        pop     esi
        add esp, 12
        pop ebp
        ret     0
_viterbi_mmx    ENDP
END
```

Example 6. C Code Listing

```
#include <stdio.h>
#include <stdlib.h>
/* HI is a large value used for padding data structures. Effectively this will be
 * a "dont care" when taking the minimum in the Viterbi function.
 */
#define HI 0xFFFF
/* Return the minimum of two integers. Note the macro __min can be used
 * directly if attention is paid to the parenthesis in the arithmetic
 * expressions.
 */
int imin(int a, int b)
{
        int i;
        i = __min(a, b);
        return i;
} /* imin */
/* Function template for the Viterbi MMX function call */
```

```
int viterbi_mmx(unsigned int *obsVect, int obsLen, unsigned int *aProb,
        unsigned int **bProb, unsigned int *pi, int nStates, int *distBuffer);
/* C implementation for the Viterbi function for discrete HMMs. The arguments are
 * described briefly here but described in detail in the accompanying application notes.
 * obsVect is the vector of VQ indices corresponding to the continuous observations
 * obsLen is the length of the observation
 * aProb is the vector of transition probabilities (format described in the appliation notes)
 * bProb is the matrix of output probabilities. bProb points to a vector of pointers to row
 * vectors. Each row index corresponds to the VQ index and each column index corresponds to
 * the state number.
 * pi is the vector of initial probabilities.
 * nStates is the number of states.
 * distBuffer is used by the function for temporary storage of distances.
 */
int viterbi_c(unsigned int *obsVect, int obsLen, unsigned int *aProb,
        unsigned int **bProb, unsigned int *pi, int nStates, int *distBuffer)
{
        int i, j, minDist;
        int *Dist = distBuffer;
        unsigned int *b, *aProbTemp = aProb;
        int nCount, nRemain;
        /* Initialiazation */
        for (i = 0; i < nStates; i++) {
                Dist[i] = pi[i] + bProb[obsVect[0]][i];
        }
        /* nCount will contain the number of times to execute the main loop
         * which processes four states at a time. nRemain contains the number
         * of states remaining after processing four at a time (i.e. 0, 1, 2 or 3)
         */
        nCount = nStates >> 2;
        nRemain = nStates - (nCount << 2);
        /* Iterate through each observation (i.e. increment time index) */
        for (i = 1; i < obsLen; i++)
        {
                b = bProb[obsVect[i]];
                Dist = distBuffer;
                aProb = aProbTemp;
                /* Process four states at a time */
                for (j = 0; j < nCount; j++) {
                        Dist[0] = b[0] + imin(Dist[0] + aProb[0], imin(Dist[1] + aProb[2],
                                Dist[2] + aProb[4]));
                        Dist[1] = b[1] + imin(Dist[1] + aProb[1], imin(Dist[2] + aProb[3],
                                Dist[3] + aProb[5]));
                        Dist[2] = b[2] + imin(Dist[2] + aProb[6], imin(Dist[3] + aProb[8],
                                Dist[4] + aProb[10]));
                        Dist[3] = b[3] + imin(Dist[3] + aProb[7], imin(Dist[4] + aProb[9],
                                Dist[5] + aProb[11]));
                        /* Update addresses for the nex four states */
                        Dist = Dist + 4;
                        b = b + 4;
                        aProb = aProb + 12;
                } /* for */
                /* Process the remaining states if any (1, 2 or 3 remaining states) */
                switch (nRemain)
                {
                        case 3 :
                                {
                                Dist[0] = b[0] + imin(Dist[0] + aProb[0], imin(Dist[1] +
aProb[2],
                                        Dist[2] + aProb[4]));
                                Dist[1] = b[1] + imin(Dist[1] + aProb[1], imin(Dist[2] +
aProb[3],
                                        Dist[3] + aProb[5]));
                                Dist[2] = b[2] + Dist[2] + aProb[6];
```

```
                                break;
                                }
                        case 2 :
                                {
                                Dist[0] = b[0] + imin(Dist[0] + aProb[0], Dist[1] +
aProb[2]);
                                Dist[1] = b[1] + Dist[1] + aProb[1];
                                break;
                                }
                        case 1 :
                                {
                                Dist[0] = b[0] + Dist[0] + aProb[0];
                                break;
                                }
                } /* case */
        } /* for */
        /* Find the return the minimum distance in distBuffer */
        Dist = distBuffer;
        minDist = distBuffer[0];
        for (i = 1; i < nStates; i++)
                if (Dist[i] < minDist)
                        minDist = Dist[i];
        return minDist;
} /* viterbi_c */
/* Return TRUE if argument is an even number, else FALSE */
int evenP(int n)
{
        return (n == ((n >> 1) << 1));
}
#define maxStates 20
#define nSymbols 3
/* Main program to test viterbi_c and viterbi_mmx for small datasets */
void main(int argc, char *argv[]){
        unsigned int b0[maxStates], b1[maxStates], b2[maxStates];
        unsigned int aProb[3 * maxStates];
        unsigned int *bProb[nSymbols] = {b0, b1, b2};
        unsigned int pi[maxStates];
        unsigned int obsVect[2*maxStates];
        int distBuffer[maxStates + 2];
        int dist_mmx, dist_c, i;
        int nStates, obsLen;
        /* Create the datasets and fill in aProb, bProb, pi, and obsVect */
        for (nStates = 1; nStates <= maxStates; nStates++)
        {
                for (i = 0; i < nStates; i++)
                {
                        b0[i] = i + 1;
                        b1[i] = i + 3;
                        b2[i] = i + 5;
                        pi[i] = HI;
                } /* for */
                pi[nStates - 1] = 0;
                obsLen = 2 * nStates;
                for (i = 0; i < obsLen; i++)
                        obsVect[i] = i % nSymbols;
                if (evenP(nStates))
                {
                        for (i = 0; i < nStates * 3; i++)
                                aProb[i] = i + 1;
                        aProb[nStates*3 - 1] = HI;
                        aProb[nStates*3 - 2] = HI;
                        aProb[nStates*3 - 3] = HI;
                }
                else
```

```
                {
                        for (i = 0; i < (nStates - 1)*3; i++)
                                aProb[i] = i + 1;
                        aProb[(nStates - 1)*3 - 1] = HI;
                        aProb[(nStates - 1)*3] = (nStates - 1)*3 + 1;
                }
                distBuffer[nStates] = HI; distBuffer[nStates + 1] = HI;
                dist_mmx = viterbi_mmx(obsVect, obsLen, aProb, bProb, pi, nStates,
distBuffer);
                distBuffer[nStates] = HI;  distBuffer[nStates + 1] = HI;
                dist_c = viterbi_c(obsVect, obsLen, aProb, bProb, pi, nStates, distBuffer);
                printf(" nStates = %3d, mmx_dist = %6d, c_dist = %6d \n", nStates, dist_mmx,
dist_c);
        } /* for */

        getchar();
} /* main */
```